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Simulation-based assessment of aggregated residential energy demand reduction strategies for cooling in a South Indian community

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Abstract

According to India Energy Security Scenario 2047, residential air conditioners (A/Cs) will increase from 21.8 million in 2017 —about 8% of the Indian households—to approximately 154.4 million in 2037. As a result, according to Indian Cooling Action Plan (ICAP), the associated electricity consumption is likely to quadruple in the next two decades. Therefore, the study of demand reduction or management strategies for cooling is essential to reduce and manage the projected significant electricity demand. The strategies might influence formulating and implementing climate-specific cooling policies at the state and country level, and to adopt new low-energy and low-cost cooling technologies at mass-market scale. Under the high electricity demand for cooling projections of India, the objective of this study is to investigate the increase in A/C use on the aggregated consumption as well as to assess the performance of residential cooling demand management strategy (load shifting) on the reduction of peak electricity demand load of part of a community (Auroville) in Southern India. The analysis showed that the elevated ownership of A/C might increase average daily electricity demand ~6.6 times than that of the base case scenario of using all-electric fans for attaining thermal comfort. The mixed-mode uses of A/Cs and fans created a demand management opportunity through load shifting which demonstrated ~46% reduction (for 15 min shift of 50% household A/C use) potential for aggregated electricity peak loads.

Introduction

World's second-largest populous country India (WB, 2019), has one of the highest amounts of Cooling Degree Days (CDDs) globally (Sivak, 2009) predominantly due to geographical location and the adverse effects of climate change. Therefore, India has the highest amount of population under the heat stress caused by climate change (Biardeau, Davis, Gertler, & Wolfram, 2020). On the other hand, India has one of the lowest amount (8% in 2017 (GoI, 2015)) of air conditioning (A/C) units in households which is significantly lower as compared to China (60%) and USA (90%) (IEA, 2019). Also, the affluence of the middle-class population of India is rising rapidly due to economic development in recent years. Hence, it is estimated that, under the elevated global temperature scenarios, the number of A/C units in Indian households may increase 42 times (1144 million units) by 2050 as compared to 2016 (27 million units) (IEA, 2019).

The elevated demand for cooling for attaining thermal comfort with the affluent middle class may increase the demand of electricity significantly. Majority of the A/Cs used in India are 3-star now (Desikan, 2019), although there are also 4-star and 5-star rating A/Cs. The energy efficiency level of the 3-star rating A/Cs are low and consumes higher electricity. International Energy Agency (IEA) showed that 10.5% of the peak electricity demand in India in 2016 might rise to 44.1% by 2050 under the baseline scenario. However, the peak demand share can be reduced to 19.3% under efficient cooling scenario (IEA, 2019).

The Government of India recognised the significance of cooling in the future and adopted ICAP in 2019 which showed that the room A/Cs will be 50% of the building sector's cooling energy demand of 600 TWh by 2037–2038 (GoI, 2019). Also, ICAP denotes a significant presence (~40% (GoI, 2019)) of non-refrigerant based cooling from air coolers — evaporative cooling from passing air over water — and electric fans. ICAP aims at reducing cooling electricity demand across sectors by 20–25% by 2037–2038 (GoI, 2019) as well as improving the A/Cs efficiency and development of sustainable technologies.

There have been several studies on the residential sector electricity consumption of India (Murthy, Sumithra, & Reddy, 2001; Filippini & Pachauri, 2004; Dhar, Srinivasan, & Srinivasan, 2018; van Ruijven, et al., 2011). However, very few studies took India's household-specific data-driven approach to analyse the residential electricity consumption, particularly for analysing the effect of cooling behaviour on aggregated electricity demand to attain thermal comfort. In this study, the objective was to assess the performance of residential cooling demand management strategy (load shifting) on the reduction of peak electricity demand load of a community (Auroville) in south India. The study is novel because of two reasons. First, the energy demand monitoring and analysis reveals the context-specific demand for cooling, which then feeds into the base model development for the monitored households. The output showed a baseline building physics model for assessing various future scenarios in individual building and community scale. Secondly, our present work and literature already suggest that cooling might become the most significant energy intensive appliance in the residential sector in the studied area. The cooling demand reduction assessment will show the effectiveness of load shifting on the aggregated peak electricity consumption on the community scale. Quantifying the potential for change within a modelling framework is vital for communities which, for reasons of climate, demographics and technology, are expected to see steep rises in space cooling in the coming decades.

The research will further be used to inform the work of the Community-scale Energy Demand Reduction in India (CEDRI) project (funded by DST in India and EPSRC in the UK), to combine energy network and building modelling with behavioural studies to tailor demand reduction strategies for Indian communities.

Methodology

Among the five climate zones in India, this study focuses on the warm-humid climate in south India —a community of Auroville as a case study— where summer and wintertime temperature can be 25-35°C and 20-30°C, respectively, with relative humidity 70-90%. The study had three major parts. Initially, the climate data for 1987-2019 of the Auroville was analysed to see the prevalence of heat stress. Secondly, the electricity consumption was monitored to understand the cooling behaviours of the occupants in 18 selected households for about a year. Based on the monitored data and the empirical data of the residential buildings, the building physics model (with Designbuilder) of a community (multi-storey apartment with 15 households) was constructed. Then the building model was calibrated through a manually iterative process. In the second stage, demand management and reduction strategy — load shifting due to mixed-mode use of an electric fan and A/C for attaining thermal comfort— based on monitored data were created. The peak cooling electricity demand reduction strategies were assessed within the simulation environment (with EnergyPlus) to find out the effect of mixed-mode cooling induced load shifting on aggregated electricity demand of a residential community building. EnergyPlus was selected as the simulation environment as it was previously used in a significant number of studies regarding building physics and thermal comfort such as (Xu, Taylor, & Pisello, 2014; Yoon, Baldick, & Novoselac, 2014; Al-janabi, Kavgic, Mohammadzadeh, & Azzouz, 2019; Huang & Wu, 2019).

Climate analysis: Heat stress

For the heat stress analysis of the climate of Auroville, the 30 years' weather data (1989-2019) were obtained from the Meteoblue database (www.meteoblue.com). The ambient temperature and relative humidity data were used to calculate the hourly heat index (HI) with the following equation adopted from (Rothfusz & Headquarters, 1990):

$$
\begin{aligned}
HI = & -42.379 + 2.04901523T + 10.14333127R \\
& - 0.22475541TR \\
& - 6.83783 \times 10^{-3}T^2 \\
& - 5.481717 \times 10^{-2}R^2 \\
& + 1.22874 \times 10^{-3}T^2R \\
& + 8.5282 \times 10^{-4}TR^2 \\
& - 1.99 \times 10^{-6}T^2R^2
\end{aligned}
$$

Where, T = ambient dry bulb temperature (°F)
R = Relative humidity (integer percentage).
HI was selected for the study as it has been widely used in several studies to analyse the adverse effect of heat stress. For example, Opitz-Stapleton, S. et al. (2016) investigated potential changes in day and night-time ambient temperatures and heat indices in Vietnam for 2020–2049 as compared to 1970–1999 by using HI index analysis (Opitz-Stapleton, et al., 2016). There were other studies which also used HI, such as (Luo & Lau, 2019; Modarres, Ghadami, Naderi, & Naderi, 2018; Choi & Lee, 2020).
For the analysis in this study, we converted the ambient dry bulb temperature into °C with the following equation adopted from (Fay & Hardie, 2003):

$$C = 5/9\,(F - 32)$$

Where, C= ambient dry bulb temperature (°C)
F= ambient dry bulb temperature (°F)

Monitoring household electricity consumption

Auroville is an experimental township established in 1968 in Southern India (Auroville, 2017). For the monitoring, three buildings in Auroville were selected where 21 and 9 households were chosen to be observed in Citadines (I and II) and Inspiration, respectively. Each household had an electricity meter which usually showed an alternating current (AC) static energy (Wh) consumption of the household, as well as there, was an external light-emitting diode (LED) which "blinks" each time a certain amount of energy was consumed. 'Blink meters' were installed on top of the LED lights of the electricity meters of the selected households. The single-phase meters were of 16,000 blinks/kWh specification —i.e., 0.06 Wh/blink— and three-phase meters had blink resolution of 800 blinks/kWh (1.25 Wh/blink). As the blink meters rely on the blinks, which depends on the specific amount of electricity to be consumed, the monitored electricity consumption data in each candidate dwelling using blink meters had irregular timestamps. The detail description of the monitored buildings and the appliances in the households were elaborated in (Debnath, Jenkins, Patidar, & Peacock, 2020). The household electricity consumption data was collected for November 2018- June 2019.

Data analysis

The household electricity consumption data were collected with blink meters. Due to the constraints such as load shedding, technical issues, blink meter specification and human factors, the collected data had gaps. The data collection procedure were described in detail, as well as the data constraints in (Debnath, Jenkins, Patidar, & Peacock, 2020). To circumvent the missing data issues, we used the 'Missing Data Filling' methodology described in (Debnath, Jenkins, Patidar, & Peacock, 2020). We used the synthesised 1-minutely electricity consumption data of the households to extract the representative cooling appliance operation schedule, which is elaborated in the subsection ‘Cooling appliance operation schedule’.

Building physics modelling of the community

The 4-storied Citadine-1 building in Auroville with 15 households (with ~50-100 m^2 area) was modelled (as shown in Figure 1) in Designbuilder with constructions and materials described in Table 1. Also, from the energy audit of the households, the electricity use for other appliance use apart from Heating, Ventilation, Air Conditioning (HVAC) and lighting appliances were 7.5-27.1 kWh/m^2 and average 13.66 kWh/m^2, after omitting the outliers average 10.34 W/m^2 (assuming on average 1.5 hours use daily) was used in the simulation. For each fan and A/Cs, 75 W and 32.85 kWh/m^2 were used, respectively. In the case of lighting, the energy use was 0.005 W/m^2 for the simulation.

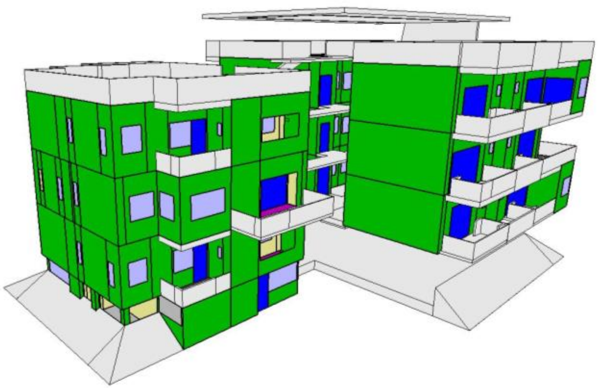


Figure 1: (Top) The picture of the modelled and monitored Citadine-1 building; (Bottom) Building physics model developed in Designbuilder (Version 6.1.5.004)

Table 1: Construction name, thickness and materials; for the material properties, software database were used.

Name	Thickness (m)	Materials	U-Value (W/m^2-K)
Exterior walls	0.28	Lightweight brick masonry with 0.15m cement plaster on both sides	0.675
Internal walls	0.15	Lightweight brick masonry with 0.15m cement plaster on both sides	2.301
Roof	0.13	Cast Concrete (Dense)	3.857
Windows	0.005	Glass windows with aluminium frames.	1.978
External doors	0.04	Plywood (Heavyweight)	2.479
Internal doors	0.04	Plywood (lightwood)	2.479

Scenario development

The A/C ownership has been increasing rapidly in Auroville (Osunmuyiwa, Payne, Ilavarasan, Peacock, & Jenkins, 2020). The analysis of the electricity consumption showed a mixed-mode use of A/C and electric fans in the households with A/C (Debnath, Jenkins, Patidar, & Peacock, 2020). The extensive use of electric fans for attaining thermal comfort in India was also evident in (Indraganti, 2011; Indraganti, 2010). Therefore, it may offer an opportunity for load shifting to reduce the effect of peak electricity consumption. For the study, the following scenarios were selected:

- All households with only electric fans for attaining thermal comfort (Baseline);
- All households with A/C and electric fans for attaining thermal comfort (Highest demand);
- All households with A/C and electric fans but with 15-minute load shifting schedules (Reduced peak).

Results and discussion

Climate analysis: Heat stress in Auroville

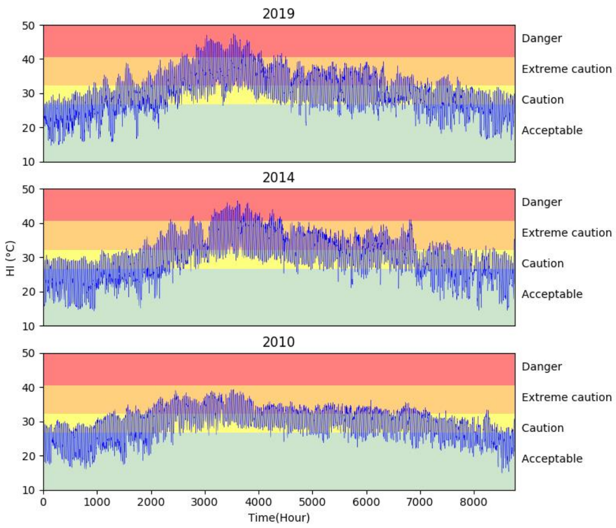


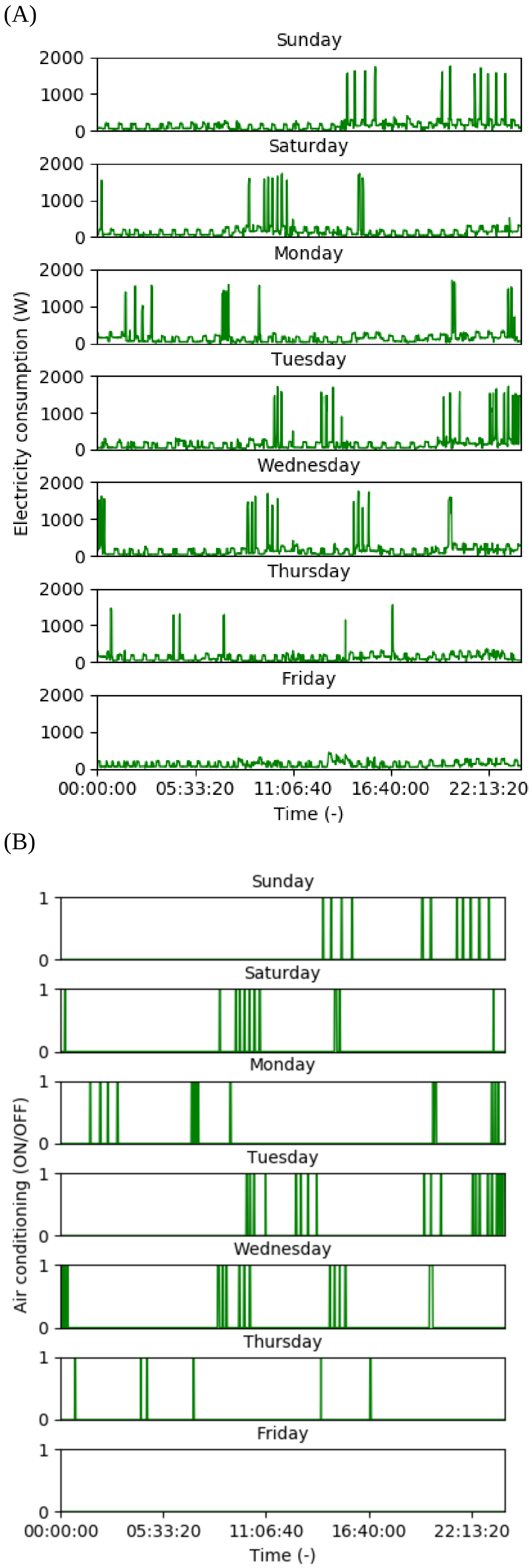
Figure 2: Hourly HI analysis of 2019, 2014 and 2010. The HI levels were adopted from (NWS, 2020).

The heat index (HI) analysis of 2010, 2014 and 2019 was demonstrated in Figure 2. The HI during summer 2010 was in extreme caution level, whereas since 2014 the HI during summer regularly crossed into danger level. In 2014 and 2019, the HI was in Danger class which may cause likely heat cramps or heat exhaustion, even possible heatstroke with prolonged exposure and physical activity (NWS, 2020). The effects of Extreme caution are severe as described in (NWS, 2020), where the majority of the HI hours of Auroville demonstrated. High prevalence of HI in extreme caution and danger, as compared to 2010, showed that the climate of Auroville has been getting warmer and elevating the risks of heat-related health risks which may be contributing to the increase in A/C ownership in the community, as most the residents of Auroville get the electricity for free (Nagy, 2018).

Cooling appliance operation schedule

Figure 3A demonstrated the daily electricity consumption monitored households with an A/C. More than 500W in the demand profile were an indication of the use of A/C as the A/C power consumption was 1000W in B. There was only one Iron in the household, which was used much less frequency than that of A/C. The occupant used a fan after using A/C to maximise the use of cooled air in a Figure 3B mixed-mode, which is visible in the Figure 3A profile.

The electricity consumption showed another cyclic pattern between 170W and 30W which most likely represent the refrigerator cycle profile. The household had only one refrigerator. Also, the household had two electric fans of 75W each in the bedroom and living space, and a 25W exhaust fan in the kitchen. The consumption profile between 170W and 500W were extracted as demonstrated in Figure 3C to extract the operation schedule for electric fan from the electricity consumption.



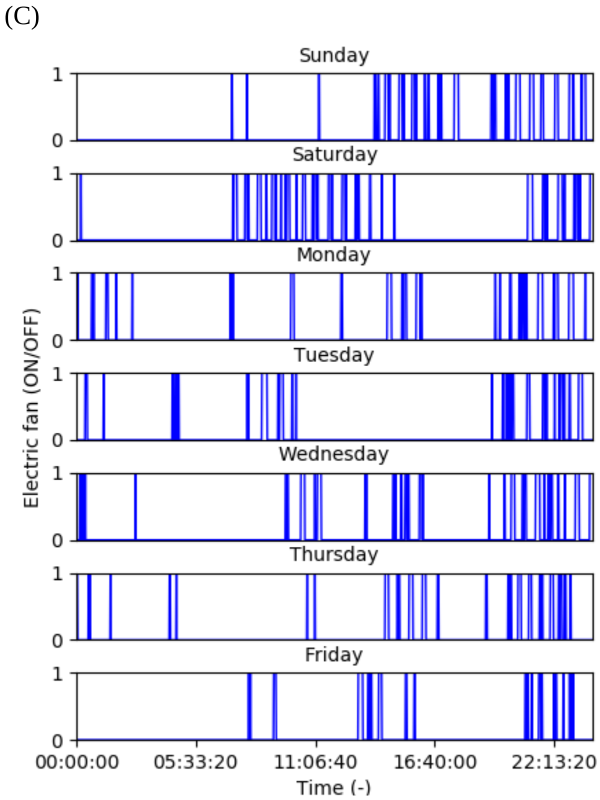
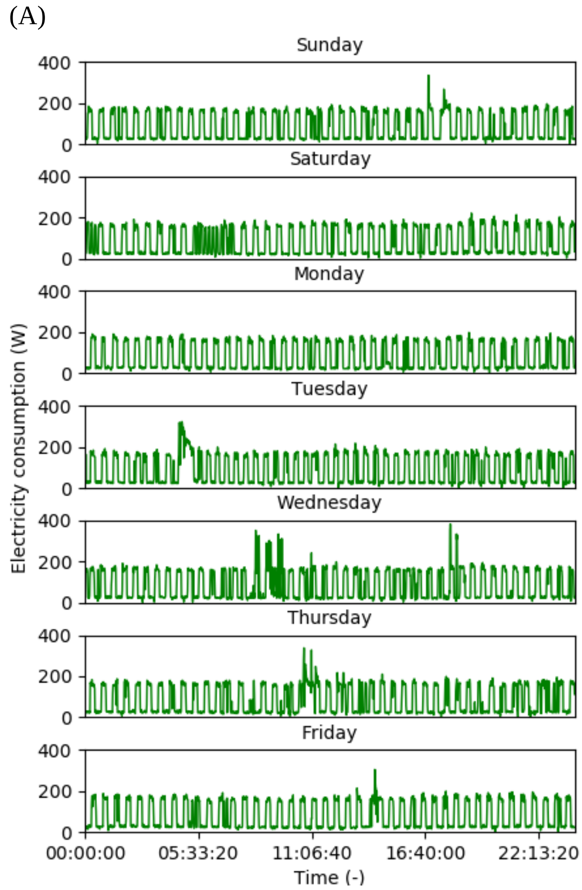


Figure 3: (A) Electricity consumption profile of 3-9 November 2018 for a household with A/C and electric fans for attaining thermal comfort; (B) A/C unit operation for retaining thermal comfort in the same household on 3-9 November 2018; (C) Electric fan operation in the same household on 3-9 November 2018.

From Figure 3B&C, electric fans were used between A/C operation. Also, the significant times of fan and A/C use were 07:00–11:15 (mornings), 12:00–17:00 (afternoon) and 19:00–01:00 (night). Also, our annual analysis showed that the A/C use was absent during December, January and February, but the fans were operational.

The households with no A/C, more or less, demonstrated very low and similar electricity consumption profiles. Figure 4A demonstrated the demand profile of a household which only had two electric fans (75W each) for mechanical ventilation to attain thermal comfort. The household had a refrigerator, and the profile shows a 30-170W cycle similar to the household with A/C. After extracting the profile of more than 170W, the daily electricity consumption comprises fan operation predominantly, as shown in Figure 4B. The operation of fans demonstrates a higher usage than that of mixed-mode, which were also verified by the occupants (Figure 3B&C). To attain thermal comfort, households with only fans operated fans for longer duration as flowing air can only ensure comfort, whereas, in the case of households with A/C, the occupants use the A/C to cool the air and the used fans to circulate until the next cycle of cooling needed.



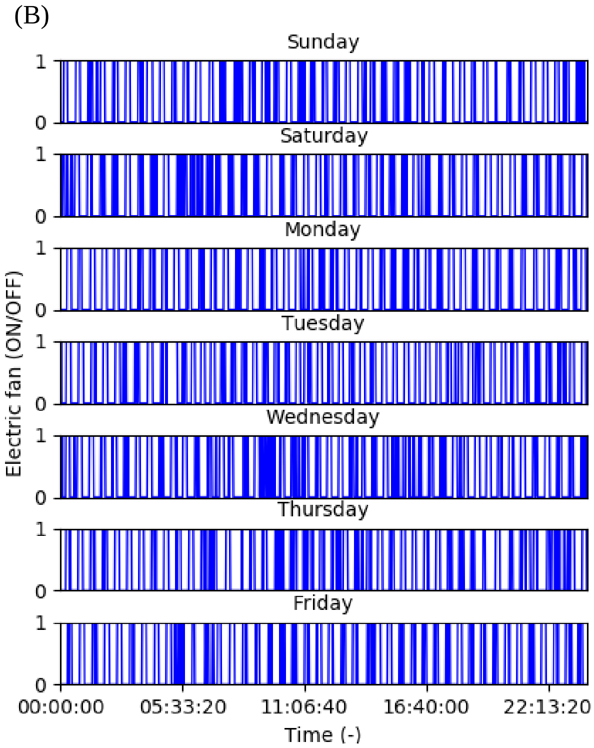


Figure 4: (A) Electricity consumption profile for a household with only electric fans for attaining thermal comfort on 3-9 November 2018. (B) Electric fan operation in the same household on 3-9 November 2018.

Model validation

With the energy audit and the electricity consumption schedules form the monitored households, the households were simulated and validated with the monitored data. Figure 5 demonstrated the monitored and simulated electricity demand pattern 1-minutely for a household with fans and no A/Cs for 3-9 November. The average of monitored electricity consumption was 0.0014 kWh for the week, and the simulation average was 0.0021 kWh. The difference was higher due to the data collection constraints and limitation of extracting electricity consumption data of appliances as well as the simulation process constraint in simulating the real-world context as described in (Royapoor & Roskilly, 2015).

Furthermore, the monitored and simulated residential building was situated in a rural area and surrounded by vegetation, which may affect the thermal comfort but much complicated to model in a virtual simulation environment. Also, there were differences in the weather files which works with a representative climate file of the area, whereas the households were monitored during 2018-19, which demonstrated higher temperature and humidity. The difference in surrounding and modelled environment, weather file and real-time weather, as well as the stochastic user behaviour, may cause the difference in monitored and simulated electricity consumption data.

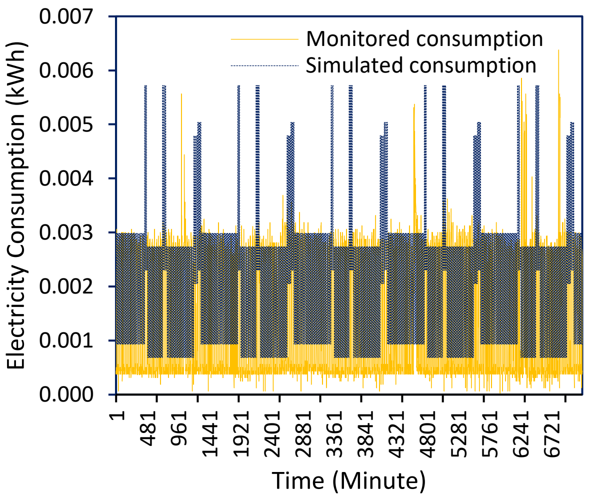


Figure 5: Minutely electricity consumption profile (monitored and simulated) for a household with fans to retain thermal comfort on 3-9 November 2018

Aggregated electricity demand for cooling and mechanical ventilation

The climate analysis showed that residents of Auroville experiences heat stress annually and the occupants of the households mentioned they preferred varied indoor temperatures even up to 28°C (Osunmuyiwa, Payne, Ilavarasan, Peacock, & Jenkins, 2020), which was significantly lower than the outdoor air temperature. In Figure 6A, results showed that during January, February and December, the outdoor temperature stayed close to an acceptable level that mechanical ventilation (predominantly with fans) may provide adequate thermal comfort. However, the fans would not be sufficient for the rest of the nine months, especially summer. A/Cs will be needed for attaining thermal comfort under the high outdoor air temperature and which also resonate with the increase in A/C ownership in Auroville.

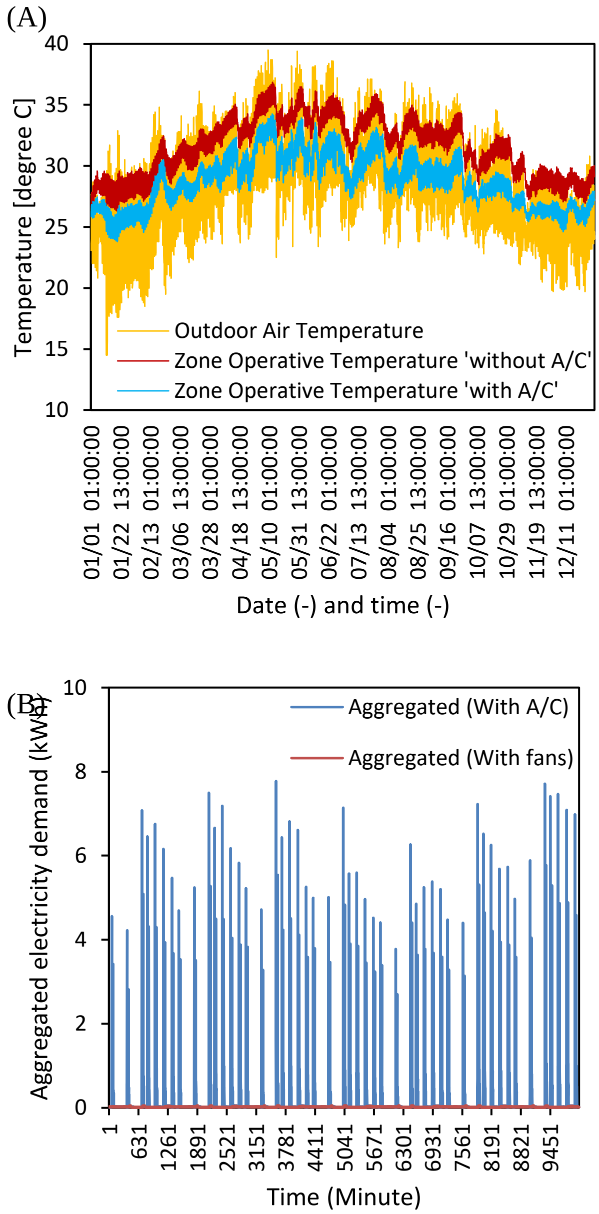
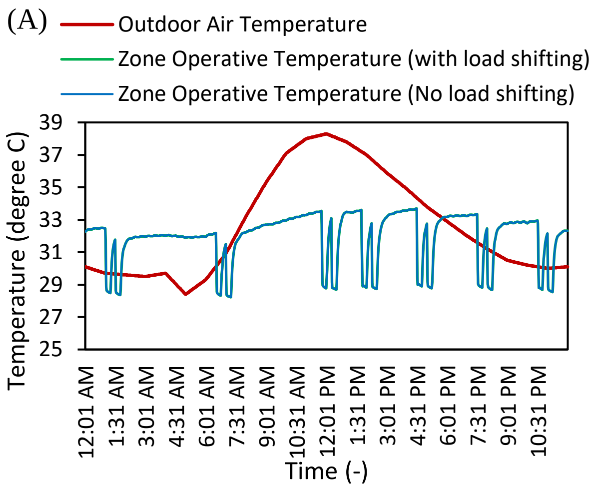


Figure 6: (A) Comparison of indoor operative temperature with and without A/C (with only fans) in a First floor flat: Bedroom and living; (B) Comparison of aggregated electricity demand with and without A/C in the building community for 3-9 November.

The high ownership of A/Cs may significantly increase the aggregated demand for electricity showed in Figure 6B. The aggregated total demand of the whole building community with 15 households with only electric fans and no A/Cs would be 117.6 kWh/week. If they all start to use A/Cs the aggregated total electricity demand increased —approximately 6.6 times — to 1170.5 kWh/week, with peak demand of 7.77 kWh (Figure 6B).

Effect of load shifting on aggregate cooling demand

As described in Figure 3A&B, the occupants with A/C used fans in combination with A/Cs to retain thermal comfort. From the profile, the fan use period between two A/C cycles ranges from 30min to 1 hour (longer during night predominantly, as the occupant may be asleep), which offers some demand management flexibility if the indoor operational temperature can be maintained.



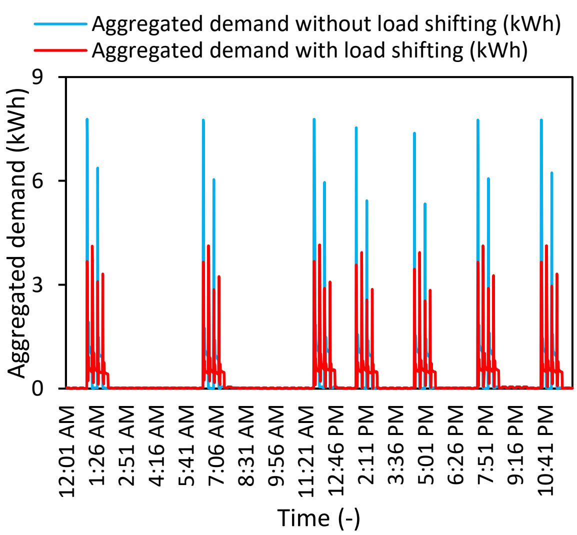


Figure 7: (A) Indoor and outdoor air temperature comparison; (B) Aggregated electricity demand with (red) and without 15-minute load shifting (blue) for 1 June in the building community.

The results showed that there would be a significant increase in terms of aggregated electricity demand under the high demand scenario with A/Cs in all households. Our simulation demonstrated that on 3 November the aggregated electricity consumption would be ~25 kWh for all 15 households with the only electric fan for thermal comfort scenario, which would rise to ~160 kWh if all households use A/Cs. The results showed that 15 min shift in 50% of the households by managing schedules of the A/Cs reduced ~46% peak aggregated load (Figure 7A) and had a minimal impact the indoor operative temperature (Figure 7B). The management of residential appliance schedules showed the significant potential of peak load reduction such as washing machine, dishwasher A/Cs (Laicane, Blumberga, Blumberga, & Rosa, 2015; Perez, Baldea, & Edgar, 2016). In the case of Auroville, the use of A/Cs showed a significant rise in electricity consumption and peak load, which may be reduced with load shifting. Furthermore, outputs of the load shifting simulation showed a 1.3% reduction —on 1 June, the aggregated total consumption was 364.10 kWh with all households using A/Cs, which reduced to 359.40 kWh with 50% of the households with 15 min load shifting— in aggregated electricity consumption in the building community.

The load shifting flexibility in the demand offers more scope in testing more scenarios to examine the effect on the indoor operative temperature as well as the aggregated electricity demand for cooling. This study is an initial stage of developing calibrated community models to test demand reduction and management scenarios, which is a part of the Community-scale Energy Demand Reduction in India (CEDRI) project. The next stage of the study would be to create a more robust calibrated model and test more complex demand reduction and management scenarios. Another target would be to extend the community size and validate the simulated results with greater accuracy.

Conclusion

The study aimed to develop the simulation model for a community in Southern India to investigate the transitional effect of using appliances for attaining thermal comfort in a climate with high temperature. Initially, climate analysis showed an unprecedented prevalence of heat stress periods regularly since 2014 may be due to the effect of climate change. The high heat stress also may have affected the ownership of A/Cs among the occupants in Auroville have been increasing.

The results of our simulation showed that the households start using A/Cs the average aggregated electricity consumption may rise ~6.6 times weekly as compared to the use of only electric fans for attaining thermal comfort. Also, occupancy A/C use pattern offered some demand management flexibilities for the community to reduce the peak-load. A 15-minute load shift showed ~46% reduction potential in aggregated peak load while maintaining the indoor operative temperature.

Our study showed that the significant rise in aggregated electricity demand due to inevitable increase in A/C use in a community in a warm-humid climate of Southern India might offer the opportunity of demand management to reduce the peak loads. The size and nature of the simulation study were not intended for generalising community-scale conclusions for cooling demands across India or regions from individual simulations. Instead, the study was used to demonstrate a process where measured electricity consumption data combined with the contextual information of community households can be used to enhance understanding on the implications of increased A/C ownership and use on the aggregated electricity demand in a small (residential) building community. Furthermore, the results of the present study can not be inferred to a broader community or regional scale.

In the future direction of the research, we would like to run aggregated simulation studies on more varied case-studies for the community scale demand management or reduction with more elaborate and calibrated models. The presented research outputs will also further be used to inform the work of the CEDRI project (funded by DST in India and EPSRC in the UK), where the objective is to combine energy network and occupancy behavioural studies with building modelling to tailor demand reduction strategies for Indian communities.

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